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Design for structural and energy performance of long span buildings using geometric multi-objective optimization

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ABSTRACT

This paper addresses the potential of multi-objective optimization (MOO) in conceptual design to help designers generate and select solutions from a geometrically diverse range of high-performing building forms. With a focus on the long span building typology, this research employs a MOO approach that uses both finite element structural modeling and building energy simulations simultaneously to generate optimized building shapes that are not constrained to regular, rectilinear geometric configurations. Through a series of case studies that explore performance tradeoffs of enclosed arches and static overhangs in different climates, this paper shows how MOO can yield architecturally expressive, high-performing designs, which makes the process more attractive to designers searching for creative forms. It also provides new insight into specific design responses to various climatic constraints, since optimization that considers both structure and energy can shift best solutions in unexpected ways. Finally, by displaying performance results in terms of embodied and operational energy, this paper presents new data showing how considerations of structural material efficiency compare in magnitude to total building energy usage. Together, these three contributions can influence current sustainable design strategies for building typologies that have significant structural requirements.

1. Introduction

In the conceptual design of buildings, many traditional optimization methods have seen only limited application, despite the emphasis contemporary designers place on building performance. This is largely due to the complex requirements of contemporary architecture, and the fact that human intuition and judgment are still central to the design process. Even as early as the conceptual design phase, architects must simultaneously consider and prioritize a multitude of interrelated design objectives, and while an increasing number of these objectives are quantitatively measureable, many are not. Two of the most important objectives related to building performance are the embodied and operational energy used in a building's materials and operations, respectively. Often, the goals of reducing each of these quantities trade off with one another, as well as with other qualitative design goals, in unexpected ways.

1.1. Embodied and operational energy

In contemporary design, a high-performance, sustainable building has been identified as one that minimizes energy consumption throughout the four main stages of a building's lifetime: materials manufacturing, construction, use and maintenance, and end of life [1]. The International Energy Agency estimates that buildings accounted for nearly a third of total final energy consumption globally in 2013 [2], a number which includes the substantial embodied energy of building materials as well as the operational energy used to keep buildings lit, heated, and cooled. The need for a reduction in energy consumption and carbon emissions due to buildings has been well documented. In light of this, a conceptual designer could simply convert every aspect of the design to a unit of emissions and run a traditional optimization to find a single solution. However, in practice this would hamper the ability of designers to express preference, and also ignore financial constraints and other architectural complications that influence the development of a real building. As such, architects often find a pure performance optimization approach reductive, overly simplified, and deterministic, which can lead to resistance towards the adoption of optimization methods in design [3].

Furthermore, for long span roofs and other large structures with specific spatial requirements, consideration of form can dominate

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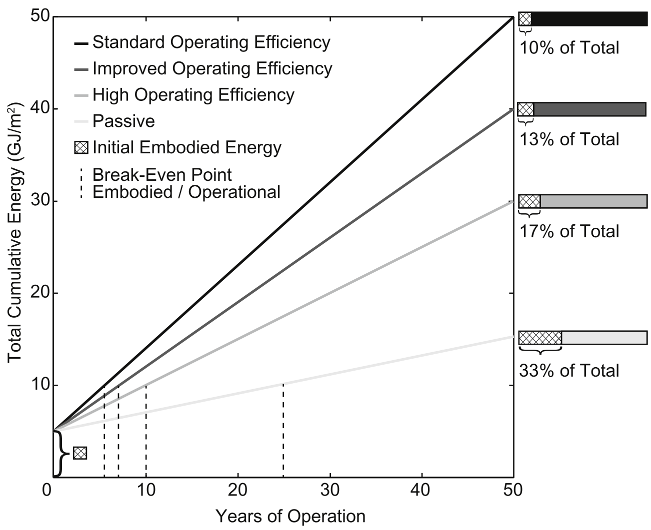

Fig. 1. The contributions of embodied and operational energy to the cumulative total energy usage of a typical building. Values from Ref. [6].

the conceptual design phase. This is especially true because structural efficiency depends more on the geometry of a building than on material, sizing, and other building characteristics developed in later stages, and because structural material makes up a more sizable portion of the overall embodied energy. For example, De Wolf [4] found that the amount of embodied energy within a building's 50-year lifecycle usage can range from 4 to 22% of the total. When considering carbon emissions instead of energy consumption, the embodied portion can rise to as high as 80% of total emissions, depending on which exact source is consulted. As shown by Kaethner and Burridge [5], the material contained in the substructure and superstructure can be responsible for over half of these embodied emissions.

With more emphasis on cutting operational energy usage while pushing towards net zero buildings, the embodied energy of future buildings will make up an increasingly larger portion of total energy usage over their lifetimes (Fig. 1) [6]. Consequently, this paper focuses on multi-objective optimization (MOO) with structural efficiency and operational energy efficiency as the two measurable objectives, since a MOO approach gives the designer flexibility but encompasses the most significant quantitative performance goals of contemporary architecture.

1.2. Multi-objective optimization

Although MOO has demonstrated a greater potential than traditional optimization to assist conceptual designers in generating and deciding between high-performing, early-stage designs, it too has seen only limited use in practice. This lack of application can be attributed to the complicated model translation that must occur between design and analysis software, the often linear process in which members of a design team are only given small latitude to 'optimize' for their own performance goals without reference to other disciplines, and the difficulty of using optimization within a process that includes subjective preferences and design goals that are difficult to formulate numerically [7]. Related fields such as aerospace, mechanical, and other pure engineering design disciplines have been more successful than architecture in overcoming some of these obstacles [8]. The differences in scale, production, and customization of buildings when compared with airplanes or cars have contributed to a building industry that is more fragmented and mostly unexposed to optimization workflows. For a conceptual MOO procedure to become popular with building designers looking for original, expressive forms, researchers must overcome difficulties of non-quantitative objectives and disconnected disciplines while showing how an integrated process can lead to a diverse range of design outcomes that meet a variety of aesthetic preferences.

Many academic researchers have addressed the limitations of multi-optimization for use in conceptual design, but few have studied the strong link between architectural form and different performance metrics simultaneously in a way that demonstrates the significant potential of MOO to influence the leading edge of architectural design. A large number of the major contributions in the field, which are described in detail and cited in the next section, have been restricted to geometries that are primarily made of rectangular boxes, which are easy to model in terms of energy usage. However, even within the typology of the long span roof, there are a wide variety of architectural forms and corresponding building shapes and structural systems that could be optimized for performance. In addition, researchers have been largely unable to define a clear way for architects to interact with MOO data, which can include performance feedback from multiple engineering disciplines in different units and scales, in a way that leads to good design decisions. In order to have greater impact on innovative and creative architectural practices, it is important to develop methodologies that effectively navigate meaningful tradeoffs and produce design examples that are applicable to a wider range of building geometries.

In response, this paper demonstrates how MOO can be used to generate geometrically diverse architectural design solutions in different climate regions through three case studies of buildings with long span roofs. Since selecting the right building shape and form in the early stages has a large effect on the overall success of a building with demanding structural and spatial requirements, the case studies focus on these large-scale conceptual design decisions.

The optimization method in this paper uses simulation to focus simultaneously on both the embodied energy found in structural material and the operational energy of the building. The case study results are presented in terms of overall energy requirements, but the embodied and operational components are kept independent since the two are not always equal when time, financing, and other practical realities of construction are taken into account. These results demonstrate the utility of separating structural efficiency (primarily upfront emissions and cost) and operational energy efficiency (emissions and cost over time) in optimization for conceptual design, as well as showing the effect of the two separate objectives on architectural form. Overall, this paper illustrates how the application of MOO can yield a wide range of expressive, high-performance designs, provides increased awareness of how architects might respond to particular climates while designing long span buildings, and contextualizes structural efficiency within the broad goals of sustainable design.

2. Literature review

2.1. Optimization for structure or energy

This research builds on a wide body of existing scholarship concerning the integration of visual criteria into optimization algorithms, geometry optimization for building performance, and multi-objective optimization in architectural design. A brief overview of major contributions is given here, beginning with research that focuses exclusively on either structure or energy usage. Mueller and Ochsendorf [9] created structureFIT, which is a browser-based conceptual design tool that allows users to progressively express preference by selecting parent structures for the next iteration of an interactive evolutionary algorithm. Coley